Modeling, Analysis and Simulation of VFT for Power Flow Control through Asynchronous Power Systems

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***Abstract*—Variable Frequency Transformer (VFT) is a controllable bi-directional transmission device that can transfer power between asynchronous networks. It avoids both HVDC link and FACTS based power transmission control system. Basically, it is a rotatory transformer whose torque is adjusted in order to control the power flow. In this paper, a simulated model of VFT is used as a controllable bidirectional power transmission device that can control power flow through the connected asynchronous power systems. A simulation model of VFT and its control system models are developed with MATLAB and a series of studies on power flow through asynchronous power systems are carried out with the model. The response characteristics of power flow under various torque conditions are discussed. The voltage, current, torque and power flow plots are also obtained.**

***Index Terms*— Variable frequency transformer (VFT), MATLAB, Asynchronous power systems, Power flow.**

I. Introduction

The world's electric power supply systems are widely interconnected. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply [1]. There are two ways of transmission interconnection. One is ac interconnection, just connected the two synchronous networks with ac transmission lines. It is simple and economic but increases the complexity of power system operation and decreases the stabilities of the power system under some serious faults. Another is Back-to-Back HVDC interconnection. The Back-to-Back HVDC is asynchronous interconnection, which is implemented via HVDC for most cases at present. It is easy for bulk power transfer and also flexible for system operation. But the design of HVDC system is quite complicated and expensive. The HVDC link requires a very costly converter plant at sending end and an inverter plant at receiving end. Alternatively recently, a new technology known as variable frequency transformer (VFT) has been developed for transmission interconnections [2-17]. By adding different devices with it, power transmission or power flow can be controlled within and between power system networks in a desired way [3].

II. Concept and COMPONENTS Of VFT

A variable frequency transformer (VFT) is a controllable, bidirectional transmission device that can transfer power between asynchronous networks [4]. The construction of VFT is similar to conventional asynchronous machines, where the two separate electrical networks are connected to the stator winding and the rotor winding, respectively. One power system is connected with the rotor side of the VFT and the another power system is connected with the stator side of the VFT. The electrical power is exchanged between the two networks by magnetic coupling through the air gap of the VFT and both are electrically isolated [4-6].

The VFT consists of following core components: a rotary transformer for power exchange, a drive motor to control the movement or speed of the rotor and to control the transfer of power. A drive motor is used to apply torque to the rotor of the rotary transformer and adjust the position of the rotor relative to the stator, thereby controlling the magnitude and direction of the power transmission through the VFT [5]. The world's first VFT, was manufactured by GE, installed and commissioned in Hydro-Quebec's Langlois substation, where it is used to exchange power up to 100 MW between the asynchronous power grids of Quebec (Canada) and New York (USA) [6].

A stable power exchange between the two asynchronous systems is possible by controlling the torque applied to the rotor, which is controlled externally by the drive motor. When the power systems are in synchronism, the rotor of VFT remains in the position in which the stator and rotor voltage are in phase with the associated systems. In order to transfer power from one system to other, the rotor of the VFT is rotated. If torque applied is in one direction, then power transmission takes place from the stator winding to the rotor winding. If torque is applied in the opposite direction, then power transmission takes place from the rotor winding to the stator winding. The power transmission is proportional to the magnitude and direction of the torque applied. When the two power systems are no longer in synchronism, the rotor of the VFT will rotate continuously and the rotational speed will be proportional to the difference in frequency between the two power systems (grids). During this operation the power flow is maintained. The VFT is designed to continuously regulate power transmission even with drifting

DOI: 01.IJEPE.02.03.23

frequencies on both grids. Regardless of power transmission, the rotor inherently orients itself to follow the phase angle difference imposed by the two asynchronous systems [2].

III. VFT Model And Analysis

A. VFT Model

In the model, the VFT is a doubly-fed wound rotor induction machine (WRIM), the three phase windings are provided on both stator side and rotor side. The two power systems (#1 and #2) are connected through the VFT as shown in Fig. 1. The power system#1 is connected to the stator side of the VFT, energized by voltage, V_S with phase angle, è$_S$. The power system#2 is connected to the rotor side of the VFT, energized by voltage, V_r with phase angle, è$_r$. A drive motor is mechanically coupled to the rotor of WRIM. A drive motor and control system are used to apply torque, T_D to the rotor of the WRIM which adjusts the position of the rotor relative to the stator, thereby controlling the direction and magnitude of the power transmission through the VFT.

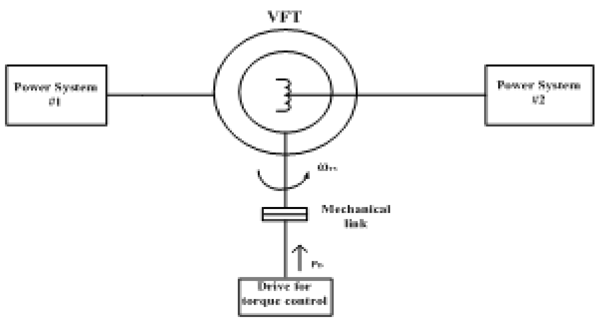

Fig. 1 The VFT model representation

It is better to represent the VFT model by an equivalent VFT power transmission or power flow model, as shown in Fig. 2. The power flow direction shows the power transmission from power system#1 to power system#2 through VFT. In fact, the direction of power flow could be from power system#1 to power system#2 or vice-versa depending on the operating conditions. If torque is applied in one direction then power flow takes place from power system #1 to power system#2. If torque is applied in opposite direction then power flow reverses as shown in Fig. 4. Here, in the power flow process, only real power flow is being discussed.

B. VFT Analysis

i) Power Flow from Power system#1 to Power system#2

The power flow through the variable frequency transformer (VFT) can be approximated as follow:

$$P_{VFT} = P_{MAX} \, Sin \, \theta_{net} \tag{1}$$

where,

P_{VFT} = Power flow through VFT from stator to rotor,

P_{MAX} = Maximum theoretical power flow possible through the VFT in either direction which occurs when the net angle ¸ *net* is near 90Ú. The P_{MAX} is given by:

$$P_{MAX} = Vs \, Vr \, / \, X_{sr} \tag{2}$$

where,

Vs = Voltage magnitude on stator terminal,

Vr = Voltage magnitude on rotor terminal and

X_{sr} = Total reactance between stator and rotor terminals.

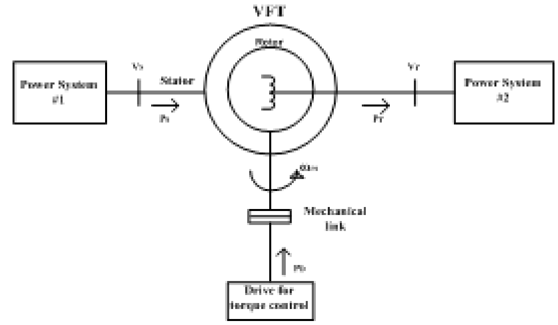

Fig. 2 Power flow from power system #1 to power system #2 using VFT

Also $$\theta_{net} = \theta_s - (\theta_r + \theta_{rs}) \tag{3}$$

where,

θ_s = Phase-angle of ac voltage on stator, with respect to a reference phasor,

θ_r = Phase-angle of ac voltage on rotor, with respect to a reference phasor and

θ_{rs} = Phase-angle of the machine rotor with respect to stator.

Thus, the power flow through the VFT is given by:

$$P_{VFT} = ((Vs \, Vr / \, Xsr) \sin(\theta s - (\theta r + \theta rs)) \tag{4}$$

The phasor diagram showing reference phasor, *Vs*, *Vr*, θ_s, θr, θ_{rs} and θ_{net} is shown in Fig. 3.

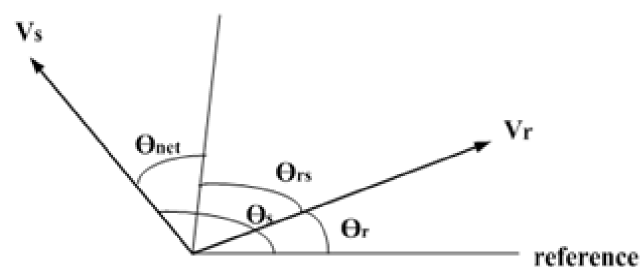

Fig. 3 The phasors of VFT

For stable operation, the angle ¸net must have an absolute value significantly less than 90Ú. The power transmission or power flow will be limited to a fraction of the maximum theoretical level given in (2). Here, the power transmission equations are analyzed based on assumption that VFT is an ideal and lossless machine, with negligible leakage reactance and magnetizing current. The power balance equation requires that the electrical power flowing out of the rotor winding must flow into the combined electrical path on the stator winding and the mechanical path to the drive system, i.e..

$$P_r = P_s + P_D \tag{5}$$

where,

P_s = electrical power to the stator windings,

P_r = electrical power out of the rotor windings and

P_D = mechanical power from the torque-control drive system.

DOI: 01.IJEPE.02.03.23

Since the machine behaves like a transformer, mmf provided by the ampere-turns of stator must balance the rotor mmf:

$$N_s*I_s = N_r*I_r \tag{6}$$

where,

N_s = number of turns on stator winding,
N_r = number of turns on rotor winding,
I_s = current to the stator winding and
I_r = current out of the rotor winding.

Both the stator and rotor windings link the same magnetic flux but their frequency differs such that the voltage will also differs by the same ratio, therefore

$$V_s = N_s * f_s * \psi_a, \tag{7}$$
$$V_r = N_r * f_r * \psi_a, \tag{8}$$
$$\text{and } V_r / N_r = V_s / N_s * f_r / f_s \tag{9}$$

where,

f_s = frequency of voltage on stator winding (Hz),
f_r = frequency of voltage on rotor winding (Hz), and
ψ_a = air-gap flux.

The nature of the machine is such that in steady state, the rotor speed is proportional to the difference in the frequency (electrical) on the stator and rotor windings,

$$f_{rm} = fs - fr\,, \tag{10}$$
$$\text{and } \omega_{rm} = f_{rm} *120/ N_P \tag{11}$$

where,

f_{rm} = rotor mechanical speed in electrical frequency (Hz),
N_P = number of poles in the machine, and
ω_{rm} = rotor mechanical speed in rpm.

Combining the above relationships gives the power exchanged with the drive system as

$$\begin{aligned} P_D &= P_r - P_s = V_r*I_r - V_s*I_s \\ &= V_r*I_r - (N_s*V_r/N_r*f_s/f_r)*(N_r*I_r/N_s) \\ &= V_r*I_r*(1 - f_s/f_r) \\ \text{or, } P_D &= P_r*(1 - f_s/f_r) \end{aligned} \tag{12}$$

It shows that the electrical power flowing out of the rotor winding being proportional to mechanical power of the drive system, stator frequency and rotor frequency. Hence, if the stator frequency and rotor frequency are kept constant, then the electrical power flowing out of the rotor winding being only proportional to mechanical power of the drive system.

ii) Power Flow from Power system#2 to Power system#1

The power balance equation requires that the electrical power flowing out of the stator winding must flow into the combined electrical path on the rotor winding and the mechanical path to the drive system, i.e.

$$Ps = P_D + Pr \tag{13}$$

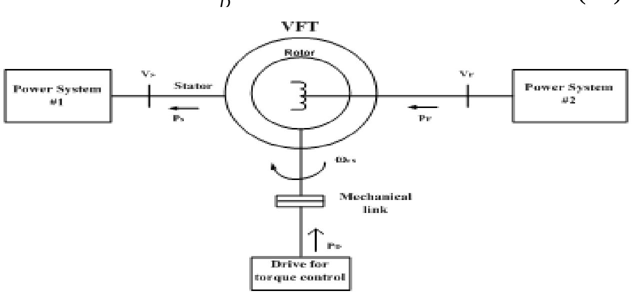

Fig. 4 Power flow from power system #2 to power system #1 using VFT

where,

P_s = electrical power out of the stator windings,
P_r = electrical power to the rotor windings and
P_D = mechanical power from the torque-control drive system.

Since the machine behaves like a transformer, the ampere-turns must balance between stator and rotor:

$$N_s*I_s = N_r*I_r \tag{14}$$

Both the stator and rotor windings link the same magnetic flux but their frequency differs such that the voltage will also differs by the same ratio, therefore

$$V_s = N_s * f_s * \psi_a, \tag{15}$$
$$V_r = N_r * f_r * \psi_a, \tag{16}$$
$$\text{and } V_r / N_r = V_s / N_s * f_r / f_s \tag{17}$$

where,

f_s = frequency of voltage on stator winding (Hz),
f_r = frequency of voltage on rotor winding (Hz), and
ψ_a = air-gap flux.

The nature of the machine is such that in steady state, the rotor speed is proportional to the difference in the frequency (electrical) on the stator and rotor windings,

$$f_{rm} = fs - fr\,, \tag{18}$$
$$\text{and } \omega_{rm} = f_{rm} *120/ N_P \tag{19}$$

Combining the above relationships gives the power exchanged with the drive system as

$$\begin{aligned} P_D &= P_s - P_r = V_s*I_s - V_r*I_r \\ &= V_s*I_s - (N_r*V_s/N_s*f_r/f_s)*(N_s*I_s/N_r) \\ &= V_s*I_s*(1 - f_r/f_s) \\ \text{or, } P_D &= P_s*(1 - f_r/f_s) \end{aligned} \tag{20}$$

It shows that the electrical power flowing out of the stator winding being only proportional to mechanical power of the drive system, rotor frequency and stator frequency. Hence, if the rotor frequency and stator frequency are kept constant, then the electrical power flowing out of the stator winding being only proportional to mechanical power of the drive system.

IV. DIGITAL SIMULATION OF VFT

A. MATLAB Simulation Model

For MATLAB, here VFT is represented as a wound rotor induction machine (WRIM). The WRIM is doubly-fed and is simulated with the asynchronous machine SI units in MATLAB Simulink [15]. The power system#1 and power system#2 are simulated with three phase voltage sources as shown in Fig. 5. The three phase voltage source 1 is connected to the stator side of WRIM and the three phase voltage source 2 is connected to rotor side of WRIM. The drive motor is simulated with constant block which gives constant torque. The torque is applied to WRIM as mechanical torque T_m. To simulate various power flow functions, other blocks are also used. The power system#1 is kept at 400V (L-L) and 60Hz whereas power system#2 is kept at 300V (L-L) and 50 Hz. Then this simulated model, as shown in Fig. 5, is used to solve electric power system using VFT. Under different torque conditions, the power flow through power system#1

DOI: 01.IJEPE.02.03.23

and power system#2 is simulated. The simulated results are shown in Table I, Table II and Fig. 6.

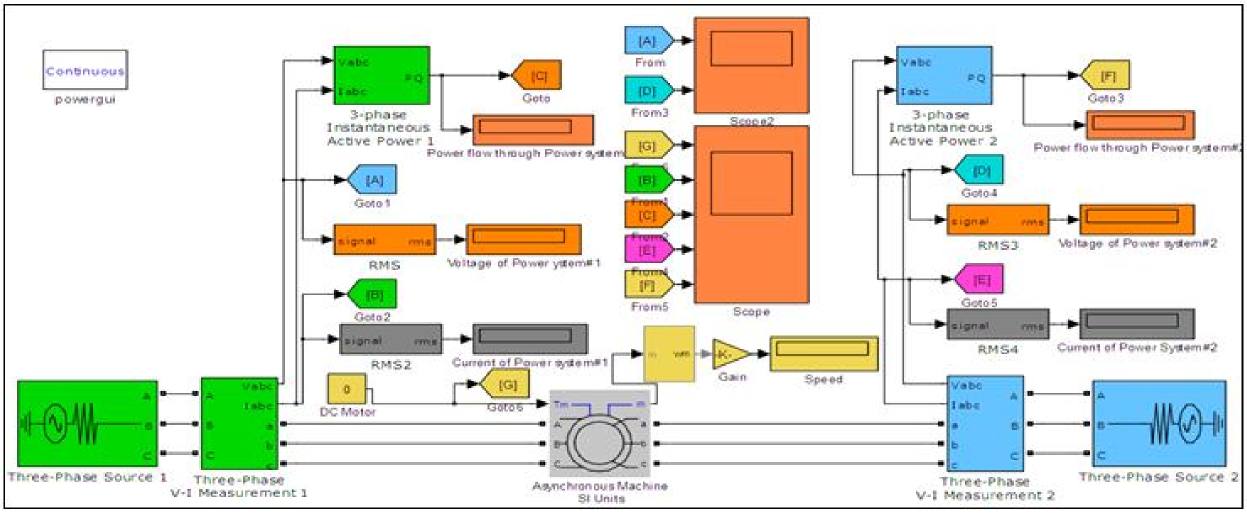

Fig. 5 MATLAB simulation model of VFT

B. MATLAB Simulation Results

i) Power Flow from Power system#1 to Power system#2

It is evident from the simulated results that under different external torque condition, the power flow through the power system#1 and power system#2 is not zero. The magnitude and frequency of voltage are kept same for all operating conditions and the power flow through power sytem#1 and power system#2 under different torque condition are shown in Table I.

TABLE I: MATLAB SIMULATION RESULTS FOR VFT

S.No	T_D (Nm)	I_S (A)	P_S (W)	I_r (A)	P_r (W)
1	0	6.813	214	3.338	36.65
2	5	5.401	1089	3.088	-781.9
3	10	4.635	2010	2.528	-1564
4	15	4.827	2967	3.096	-2304
5	20	5.871	3964	4.518	-3005

It is clear from table I that under zero torque condition the power flow through the VFT is zero even though there is power flow through power system#1 and power system#2 i.e. VFT is taking power from both the power systems. The negative sign represents the power flow towards the power system#2.

ii)Power Flow from Power system#1 to Power system#2

When the applied torque is in opposite direction then power flow direction reverses as shown in Table II.

TABLE II: MATLAB SIMULATION RESULTS FOR VFT

S.No	T_D (Nm)	I_S (A)	P_S (W)	I_R (A)	P_R (W)
1	0	6.813	214	3.338	36.65
2	-5	8.587	-624.2	4.937	901
3	-10	10.57	-1416	6.829	1808
4	-15	12.68	-2162	8.882	2763
5	-20	14.91	-2583	11.07	3768

It is clear from table II as the applied torque direction reverses the power flow direction also reverses. The negative sign represents the power flow towards the power system#1. The power flow through power system#1 and power system#2 with the applied torque achieved is shown in Fig. 6.

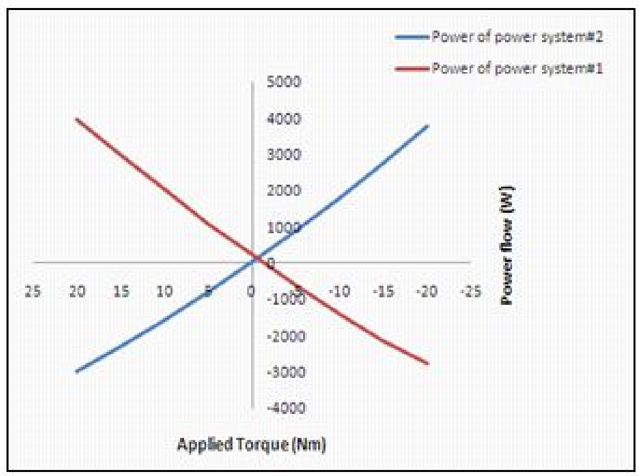

Fig. 6 The power flow with the applied torque

CONCLUSIONS

From the simulated results it is evident that both the magnitude and direction of the power flow through the connected power systems are controllable by the external torque applied to the rotor. Moreover, power flow is directly proportional to the applied torque. Hence VFT technology provides an option for achieving real power flow control through asynchronous power systems. The model developed is successfully used to demonstrate the power flow control through asynchronous power systems. The direction and the magnitude of power flow control are achieved. Thus, the VFT concept discussed and its advantages are verified by simulation results.

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DOI: 01.IJEPE.02.03.23